



Searches for Physics Beyond the Standard Model in $t\bar{t}$ Events

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Abstract. The top quark is currently only observed at the Tevatron, where it is mainly produced in $t\bar{t}$ pairs. Due to the very high mass of the top quark compared to the other quarks and the gauge bosons, it is expected to play a special role in electroweak symmetry breaking. Therefore it might be especially sensitive to new physics. Measurements of various production and decay quantities of the top quark could lead to discoveries of physics beyond the standard model. Several such measurements were performed by the CDF collaboration during Run1 of the Tevatron. These measurements and first results from CDF in Run2 are presented.

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1 Introduction

The CDF detector is a multipurpose collider experiment detector with a strong tracking system, large calorimeter coverage and muon systems. A more detailed description can be found elsewhere [1]. The top quark was discovered at the Tevatron in 1995 by both collider experiments, CDF and D0. The dominant production mechanism for top quarks at the Tevatron is via $q\bar{q}$ annihilation into a $t\bar{t}$ pair. Within the standard model (SM), the top quark decays to 100% into a W and a b quark. $t\bar{t}$ events are classified into three channels with different final state particles, depending on whether the W from the top decay itself decayed leptonically or hadronically (they are: the di-lepton, the lepton+jets and the all-hadronic channels). The number of $t\bar{t}$ candidate events that can be selected above the large background, is small (~ 60 in CDF in Run1). Therefore, the measurements of the properties of the top quark are statistically limited up to now. Measuring various production and decay properties of $t\bar{t}$ events could potentially lead to the discovery of physics beyond the SM.

In this paper we present results from several measurements probing the production as well as the decay vertex of top quarks, using CDF data from Run1. In addition we show first results from Run2, demonstrating that the top quark is seen with the extensively upgraded CDFII detector as well.

2 Kinematics of top events

Comparing various kinematical distributions of selected $t\bar{t}$ events can provide a tool to differentiate between the

SM top quark and other processes with similar final states originating from physics beyond the SM. In several such models, such as SUSY, MSSM, Technicolor etc., some of these distributions (e.g. the p_T of the top quark, the p_T and invariant mass of the $t\bar{t}$ pair, the total energy in the event, etc.) differ significantly from SM expectations for the top quark. Some of the observed features in the Run1 dataset include:

- A hint for an increase of the measured top mass, M_t , with the number of jets in the event [2]
- A slight excess of W+2jet and W+3jet events, where one jet is tagged by two different b-tagging algorithms (displaced vertex and soft-lepton-tag) [3]
- Two out of nine di-lepton events showed unusually large total transverse energy and missing transverse energy of the reconstructed final state objects [4]
- The measured $M(t\bar{t})$ distribution seems to deviate a little from the expected (by the SM) distribution [5]

2.1 Transverse Momentum of Top Quarks

Using the lepton+jets channel of $t\bar{t}$ decays, the p_T of the hadronically decaying top quark was measured [6]. By constraining the top mass to $M_t = 175$ GeV and performing a kinematic fit, 61 events were found in 106 pb⁻¹ of data in Run1. 31.9 ± 4.6 events were expected from various SM background sources. After applying an unsmearing procedure, an unbinned likelihood fit was performed to extract the true $p_T(t)$. The measured values of $p_T(t)$ are in good agreement with the SM expectations over the entire $p_T(t)$ range (see table 1). A 95 % confidence limit for high p_T top contributions was derived to be: $N_{top}(225 < p_T(t) < 425 \text{ GeV})/N_{top}(\text{all } p_T(t)) < 0.16$.

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Table 1. Relative contributions to top quark production in bins of p_T of the top quark

p_T Bin	Measurement	SM Expectation
$0 \leq p_T < 75$ GeV	$0.21^{+0.22+0.10}_{-0.21-0.08}$	0.41
$75 \leq p_T < 150$ GeV	$0.45^{+0.23+0.04}_{-0.23-0.07}$	0.43
$150 \leq p_T < 225$ GeV	$0.34^{+0.14+0.07}_{-0.12-0.05}$	0.13
$225 \leq p_T < 300$ GeV	$0.000^{+0.031+0.024}_{-0.000-0.000}$	0.025
$0 \leq p_T < 150$ GeV	$0.66^{+0.17+0.07}_{-0.17-0.07}$	0.84

2.2 Search for the SM Higgs

A search for the SM Higgs was performed using the data in the W+2jets bin. This analysis was searching for the process $p\bar{p} \rightarrow W + X + l\nu + b\bar{b}$ using 109 pb⁻¹ of Run1 data. Most of the signal is expected in the W+2jets bin of a generic top analysis. The other bins were used to cross check background expectations. This analysis required one or two b-tags in the event, of which one had to be a displaced-vertex-tag and the other could be a displaced-vertex-tag or a soft-lepton-tag. In the W+3jets bin good agreement was found between data and SM expectations, while a small excess of data was seen in the W+2jets bin. In order to increase the sensitivity of the search, the invariant mass spectra of the two jets, M_{jj} was analyzed. No resonance was seen in the data. Using a binned maximum-likelihood method and fixed QCD background and $t\bar{t}$ contributions, the number of candidate events, N_{WX} was extracted. Within the model of SM Higgs production ($p\bar{p} \rightarrow WH^0$) an upper limit was derived to be: $\sigma(p\bar{p} \rightarrow WX) \times B(X \rightarrow b\bar{b}) = [14, 19]$ pb for $M_X = [70, 120]$ GeV, statistically compatible with no Higgs signal. This measurement is about two orders of magnitude away from being sensitive to the SM Higgs.

2.3 Search for $t\bar{t}$ resonances

Using the lepton+jets sample, a model independent search for a narrow vector particle $X \rightarrow t\bar{t}$ was performed [5]. No $t\bar{t}$ resonance was found and upper limits on $\sigma \times B$ for narrow resonances was derived. Using these limits a constraint on a model of topcolor assisted technicolor ($Z' \rightarrow t\bar{t}$) was put. A narrow, leptophobic X boson was excluded with $m_X < 560$ GeV/c². The expected sensitivity for this analysis in Run2 is $\delta(\sigma \times B(Z' \rightarrow t\bar{t})) \sim 90$ fb for $m_{Z'} = 1$ TeV.

2.4 Search for a V+A contribution

By measuring the helicity of the W from the top decay, one can test if the top quark we measure indeed is the SM top quark [7]. In V-A theory about 70 % of the W are expected to be longitudinally polarized and about 30 % should be left-handed. Following V+A, the W would be 70 % longitudinal and 30 % right-handed instead. Two different methods were used to measure the

W helicity. The first one, a frame-independent method, uses the invariant mass of the W decay lepton and the b-quark from the top decay. This quantity has a distinctively different shape for V-A and V+A produced top quarks. By fitting the data distribution one can therefore extract a possible V+A contribution. Using 109 pb⁻¹ of $t\bar{t}$ di-lepton and lepton+jets events with one and two b-tags, the V+A contribution to the data was measured to be: $f_{V+A} = -0.21^{+0.42}_{-0.25} \pm 0.21$, consistent with 0. The other method is using the transverse momentum of the W decay lepton, $p_T(l)$, which has a different shape for longitudinal, left-handed and right-handed W bosons. In 106 pb⁻¹ of data the fraction of longitudinally polarized W was measured to be: $F_0 = 0.91 \pm 0.37 \pm 0.13$. This value was then fixed and the data were fitted to extract a 95 % confidence limit on the right-handed contribution: $F_+ < 0.28$. The expected sensitivity for this analysis in Run2 is $\delta B(t \rightarrow W_0) = 5.5$ % and $\delta B(t \rightarrow W_+) = 2.7$ %.

2.5 Search for a charged Higgs

In models like the 2-Higgs-doublet model or MSSM, the decay $t \rightarrow H^+ b$ competes with the SM process $t \rightarrow W^+ + b$ if $m_{H^+} < m_t - m_b$. That means that the $t\bar{t}$ production and decay provide a source of a strongly interacting, charged Higgs in the following channels: $t\bar{t} \rightarrow W^\pm H^\mp b\bar{b}$ and $t\bar{t} \rightarrow H^+ H^- b\bar{b}$. Furthermore, the weak process of direct Higgs pair production, $p\bar{p} \rightarrow H^+ H^-$ should be observed. In MSSM, the dominant decay mode for $\tan\beta > 5$ is $H^+ \rightarrow \tau\nu$. Therefore, an excess over the SM of top events with τ leptons is predicted. A direct search for the signature of τ leptons in top decays was performed [8], looking for the signature $l + \tau + \cancel{p}_t + 2jets + X$. In 106 pb⁻¹ of data four candidates were found with 4.0 ± 0.6 events expected from SM sources. An upper limit for the production of a charged Higgs within MSSM was derived as a function of m_{Higgs} and $\tan\beta$; for the decay of the Higgs $B(H \rightarrow \tau\nu) = 100$ % was assumed (see figure 1). The expected sensitivity for Run2 is $\delta(B(t \rightarrow Xb)) < 12$ %.

2.6 Search for FCNC decays

Because of the large mass of the top quark, unusual decays of top quarks might provide us with insight into the mechanism of EW symmetry breaking. A search for rare decays of top quarks was performed in the following two channels [9]: $t \rightarrow q\gamma$ and $t \rightarrow qZ$. In $t\bar{t}$ events where one top quark decays like $t \rightarrow q\gamma$ and the other one decays in the standard mode $t \rightarrow Wb$, less than one event was expected from SM background sources. One event was found in 110 pb⁻¹. This event is also kinematically consistent with the process $t\bar{t} \rightarrow W^+ b + W^- \bar{b}\gamma$, but the photon E_T is exceptionally large: $E_T = 88$ GeV. From this analysis a 95 % confidence limit was derived: $B(t \rightarrow c\gamma) + B(t \rightarrow u\gamma) < 3.2$ %. In the channel where one quark decays like $t \rightarrow qZ$ and the other one decays in the standard mode $t \rightarrow Wb$, events

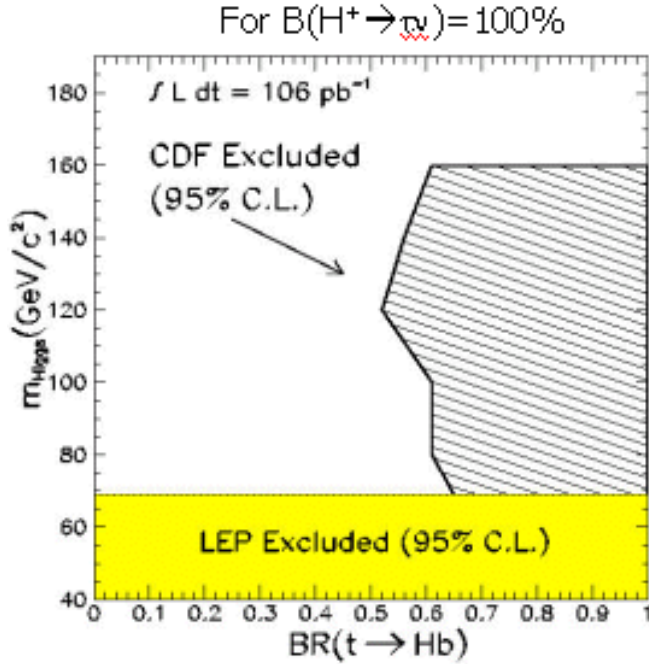


Fig. 1. The derived limit for a charged Higgs in MSSM as a function of m_{Higgs} and $\tan\beta$; $B(H \rightarrow \tau\nu) = 100\%$ assumed

involving $Z \rightarrow ee$ or $Z \rightarrow \mu\mu$ were analyzed. This channel is less sensitive than the one described above, because $B(Z \rightarrow leptons)$ is small. From SM background sources 1.2 events are expected and one event was seen in 110 pb^{-1} of data. This event is a $Z \rightarrow \mu\mu + 4\text{jets}$ event that fits kinematically better with the $Z + \text{multijets}$ hypothesis than with a FCNC decay. This result translates into a 95 % confidence limit of $B(t \rightarrow cZ) + B(t \rightarrow uZ) < 33\%$.

3 First results from Run2

About 126 pb^{-1} of Run2 data are analyzed and first cross section and m_{top} measurements were performed. The top production cross section was extracted using different methods and different decay channels. The cross section measurement using the leptons+jets channel without any b-tag requirement but event kinematics yielded $\sigma(p\bar{p} \rightarrow t\bar{t}) = 5.1 \pm 1.8 \pm 2.1$ pb when requiring three or more jets and $\sigma(p\bar{p} \rightarrow t\bar{t}) = 7.7 \pm 2.4 \pm 3.0$ pb for four or more jets in the events. The cross section measurement using the leptons+jets channel with the requirement of one or two b-tags yielded $\sigma(p\bar{p} \rightarrow t\bar{t}) = 4.5 \pm 1.4 \pm 0.8$ pb when requiring three or more jets. In the di-lepton channel two different methods gave comparable results of $\sigma(p\bar{p} \rightarrow t\bar{t}) = 7.6 \pm 3.4 \pm 1.5$ pb and $\sigma(p\bar{p} \rightarrow t\bar{t}) = 7.3 \pm 3.4 \pm 1.7$ pb respectively. The top mass was measured in the lepton+jets channel with a b-tag requirement ($m_{top} = 177.5^{+12.7}_{-9.4} \pm 7.1$ GeV/c^2) as well as in the di-lepton channel ($m_{top} = 175.0^{+17.4}_{-16.9} \pm 7.9$ GeV/c^2). All these new measurements are in good agreement with each other and with the results from Run1 data. This puts us in a situation where we can now start to perform similar

searches as described above from Run1. In fact, first limits for single top production cross section and a search for V+A contributions to top production are already on the way.

4 Summary and Conclusions

CDF has performed many interesting and promising searches for new physics in the top sector. Because of the large mass of the top quark it is suspected to play a special role in electroweak symmetry breaking. Therefore, various production and decay properties have to be scrutinized carefully in order to either confirm the SM process or physics beyond the SM. With the limited amount of data from Run1 CDF has seen many interesting results and small discrepancies in the top analyses. However, no statistically significant effect was found so far. In the currently ongoing Run2 a factor of about 50 more data are expected in the top sector. First basic measurements of top cross section and top mass show that the newly upgraded detector and the new analysis framework are well understood. High precision measurements of previously promising results will shed a clearer light on the mechanisms in the top sector. Some surprises might be found.

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